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SUPERABRASIVE INDUSTRY REVIEW

Polycrystalline Diamond (PCD) and Polycrystalline Cubic Boron Nitride (PcBN) Tooling & Applications

THIS ISSUE

News and Notes

“BEST IN CLASS” Education Course

Polycrystalline Diamond Redefines the Term “WOODWORKING”

IDA Member Companies

INTERTECH 2015 Announcement

Calendar of Events

Correlation of Failure Strength with Magnetic Properties and Material Composition of Polycrystalline Diamond

New Products

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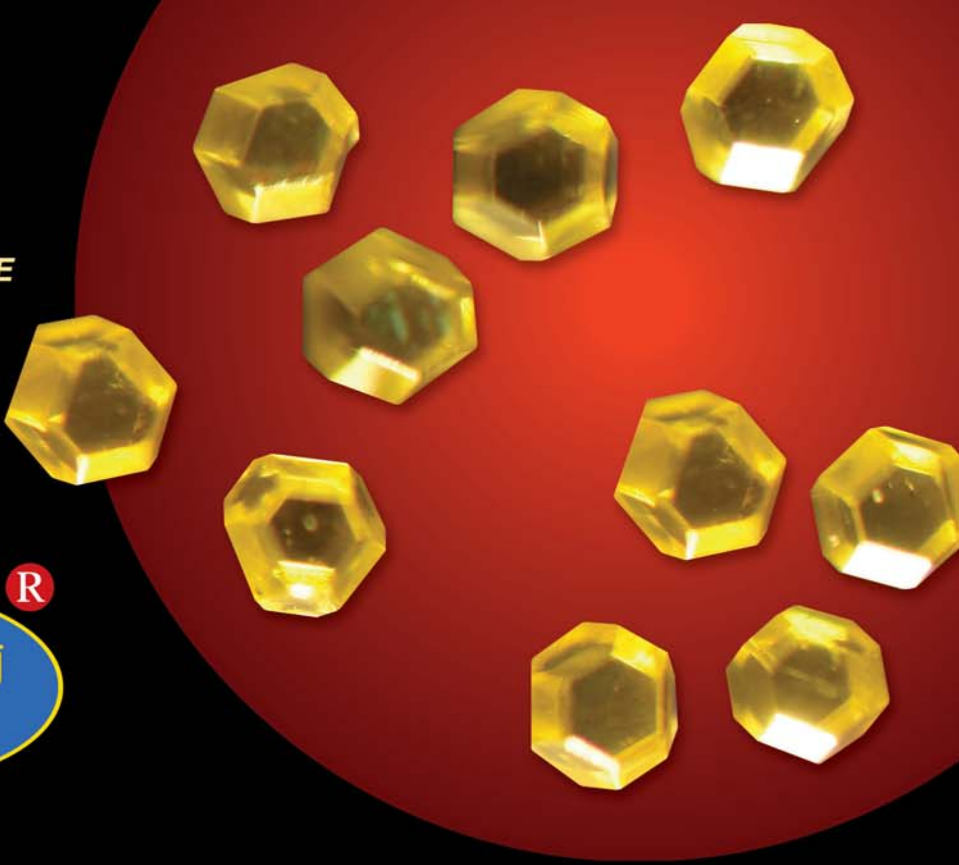

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COVER PHOTO

Photo Courtesy of Saber Diamond Tools showing Polycrystalline Diamond Cutter and Array of myriad materials in the woodworking industry.

FINER POINTS is the longest running publication devoted exclusively to the understanding, selection and application of diamond, cubic boron nitride and related materials. It is edited for recipients who are involved in some way with these "superabrasives", either as providers of the materials, producers of products containing the materials or users of these products (e.g., grinding wheels, dressing tools, drill bits, saw blades, sawing wires, cutting tools, polishing compounds, CVD film products, etc.).

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A Finer Point of View…

PRESIDENT
Troy Heuermann

In a local radio commercial, a ski shop owner stated: "When people ask me, 'Why would you train your employees? What if they leave?' I simply reply, 'What if I don't train them, and they STAY!" This particular ski shop's employees are typically twenty-something skiers and hockey players in a transitional or part time job while they go to college or start their working life. This very successful business is well known for its quality products and for its knowledgeable customer service staff.

Employees are the most critical asset to any business. Experience is the core ingredient that makes an employee effective in their job and valuable to their company. The challenge is, experienced employees are hard to find. Training begins the path towards experience by teaching people what to do, what to say or how to react. But experience requires time and application of the training and the ability to learn from positive or negative results. As my son's 7th grade teacher told us at conferences last year, "Experience is a terrible teacher because the lesson always comes AFTER the test."

It is experience though that ultimately fuels profitability, growth, productivity and innovation for our businesses and the expansion of our industry.

The Industrial Diamond Association (IDA) and its members will be sharing knowledge and experience on November 13, 2014 during a one day educational program in Huntsville, AL. The specific goal of this interactive program is to offer an opportunity for individuals to learn from the experts in the Superabrasives Industry and from each other. As a result, attendees will leave with a broader understanding of core superabrasive products, technologies and their applications in manufacturing.

Investing in the opportunity to learn from others is a great way to accelerate the steps from knowledge to experience without all the pain that makes "Experience a terrible teacher". We hope to see many of you in Huntsville.

Visit www.superabrasiveseducation.com and find all the details and register today!

Sincerely,

Troy Heuermann
Industrial Diamond Association of America

Here today…

But what about tomorrow? While hundreds of millions of Americans are enjoying the wonders of our national parks each year, the future of the very things they're coming to see is at risk. For example, although the Mexican black bear population has been slowly recovering at Big Bend National Park, their ongoing survival is threatened.

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EXECUTIVE DIRECTOR

Mr. Terry M. Kane
Industrial Diamond Association
of America, Inc.
P.O. Box 29460
Columbus, Ohio 43229
Phone: 614-797-2265
FAX: 614-797-2264

E-Mail: tkane-ida@insight.rr.com

Website: www.superabrasives.org

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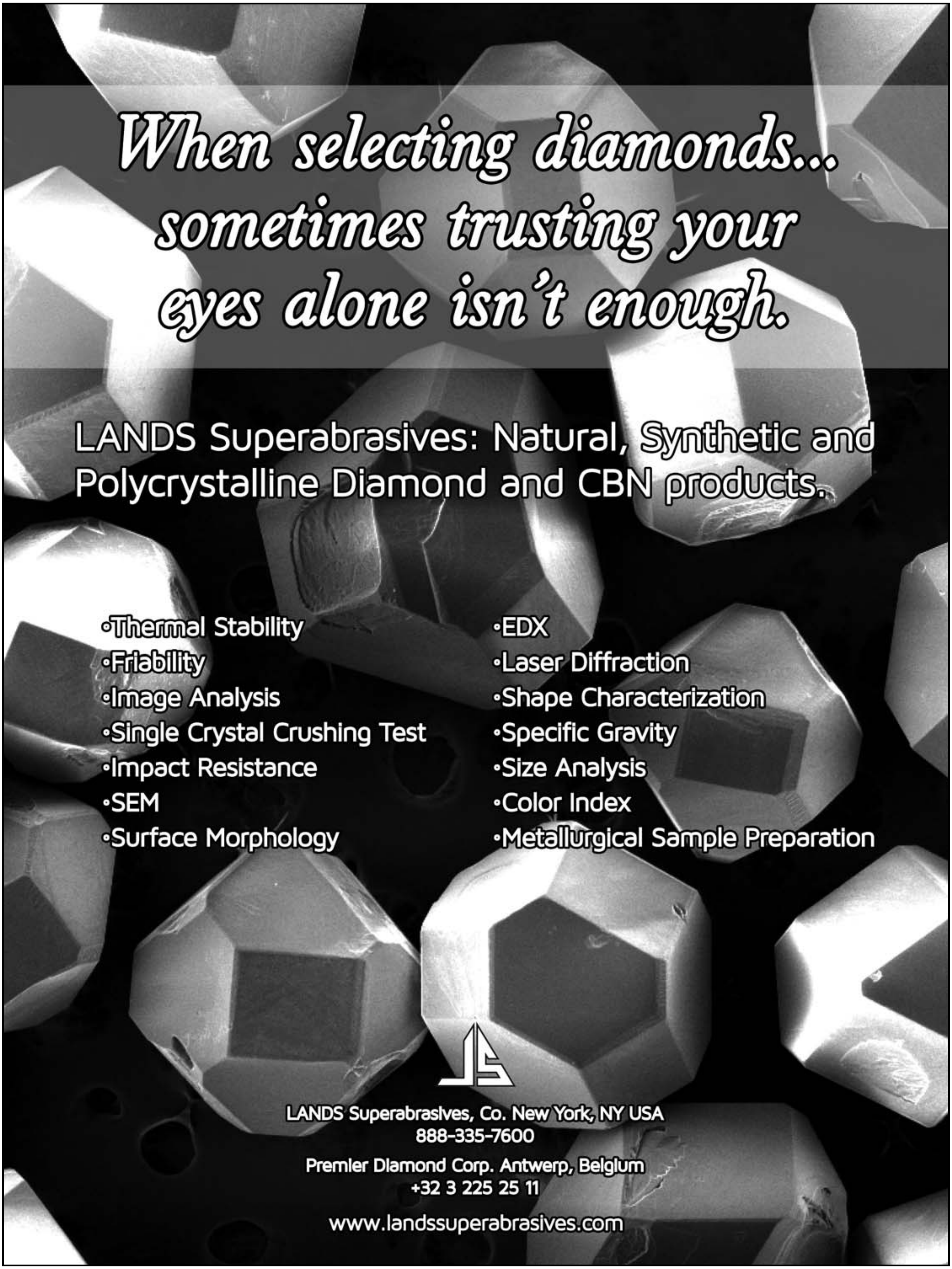

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TERRY KANE, Editor

IMTS - REALITY IS STRONGER

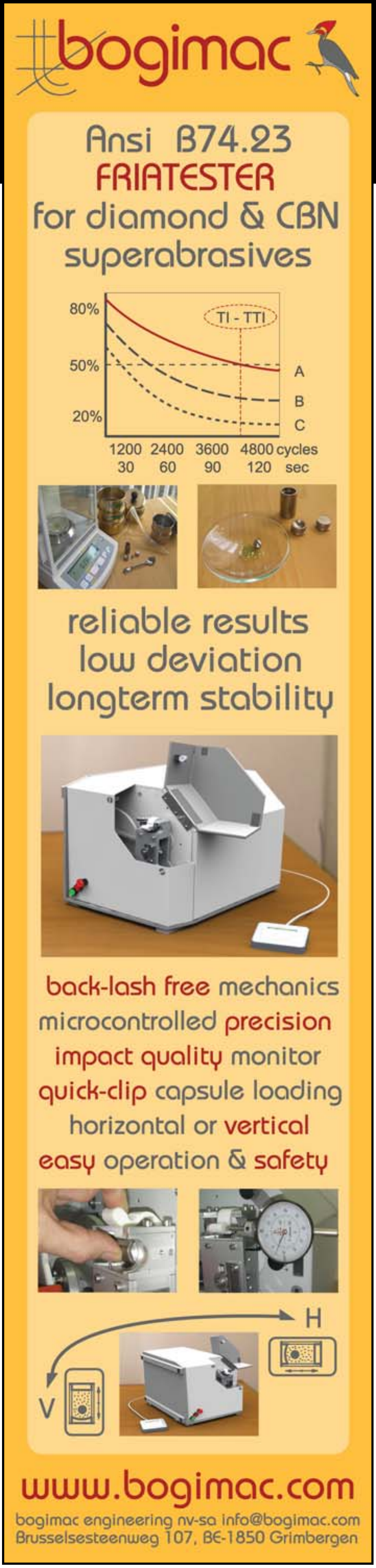
> ***"I am happy to report that in the war between reality and romance, reality is not the stronger."*** - John Steinbeck

Well, I am happy to report that I just returned from IMTS and the romance of our industry is very strong and our reality is even stronger. Those of us who started out running an old hand grinder found a certain romance with the skill it took to manipulate the multiple hand cranks to coordinate the downfeed and crossfeed with each pass to bring a part to a finished shape and dimension. It was a warm feeling to see the sparks fly and listen to the whir of the spinning wheel and the staccato of wheel meeting steel. Yes, we were artists and craftsmen and I would go so far as to say it was a romantic time. Our machines had subtle color schemes in shades of gray.

At IMTS 2014 the machines have evolved and taken on a surrealistic presence on the floor. Machines show bright color combinations of orange, red, yellow, blue, black and white polished to a high gloss to rival a new sports car! Computer screens run data and programs, lights flash, high volume coolant beats against windows, extreme spindle speeds give a low hum of activity, vacuums pull mist and chips, parts are placed by pick and place robotic systems ... Feel the love? I tend to be leaning towards the grinders, but the machining centers are just as complex and awe inspiring! IMTS has truly moved from a Machine Show to a Technology Show. Lasers were well represented and companies touting CVD Diamond, Diamond and cBN wheels and everything from polishing to sawing were all in attendance.

Of course this IMTS showed off even more technological advancements. Leading the way was AMT's Emerging Technology Center (ETC) which promised to "Wow" visitors ... and Wow it did! The ETC boasted of manufacturing "technologies of the future" from leading universities and government research labs and it did not disappoint. The number one "wow" factor in the ETC was the complete construction of a 3D-printed electric car by Local Motors which built and delivered the first direct digital manufactured vehicle in 44 hours! Designed by the company's global community, and built using the material science and advanced manufacturing techniques available at the Manufacturing Demonstration Facility (MDF) at Oak Ridge National Laboratory (ORNL), Local Motors produced an electric vehicle purpose-built for the urban transportation needs of Chicago. The team started from scratch employing direct digital manufacturing techniques and technology integration to make the parts and assemble the vehicle. This is a real-world demonstration of achieving sustainable manufacturing by using emerging technologies, such as additive manufacturing, all integrated in a digital environment. If this is the future of automotive manufacturing, you have to love the innovation ...

IMTS 2014 is one of the top three shows in the event's history. The show had about 12 percent more attendees than IMTS 2012 and they came to see the show's 2,035 exhibiting companies on the totally sold out 1,282,914 square feet of available exhibit space. Maybe Steinbeck hit the nail on the head, between reality and romance, reality is not the stronger, with all the reality at IMTS I still find a certain romance in all the new manufacturing experiences!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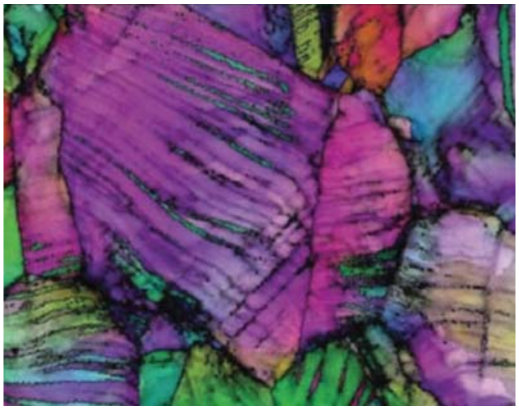
NEWS &notes

Berkeley Lab

A METALLIC ALLOY THAT IS TOUGH AND DUCTILE AT CRYOGENIC TEMPERATURES

Researchers at Berkeley and Oak Ridge Labs Test a Multi-element High-Entropy Alloy with Surprising Results

A new concept in metallic alloy design – called “high-entropy alloys” – has yielded a multiple-element material that not only tests out as one of the toughest on record, but, unlike most materials, the toughness as well as the strength and ductility of this alloy actually improves at cryogenic temperatures. This multielement alloy was synthesized and tested through a collaboration of researchers at the U.S. Department of Energy (DOE)’s Lawrence Berkeley and Oak Ridge National Laboratories (Berkeley Lab and ORNL). “We examined CrMnFeCoNi, a high-entropy alloy that contains five major elements rather than one dominant one,” says Robert Ritchie, a materials scientist with Berkeley Lab’s Materials Sciences Division. “Our tests showed that despite containing multiple elements with different crystal structures, this alloy crystalizes as a single phase, face-centered cubic solid with exceptional damage tolerance, tensile strength above one gigapascal, and fracture toughness values that are off the charts, exceeding that of virtually all other metallic alloys. Ritchie notes that the mechanical properties of CrMnFeCoNi and other high-entropy alloys have yet to be optimized. “These high-entropy alloys may well be capable of even better properties,” he says. For more, visit www.lbl.gov.



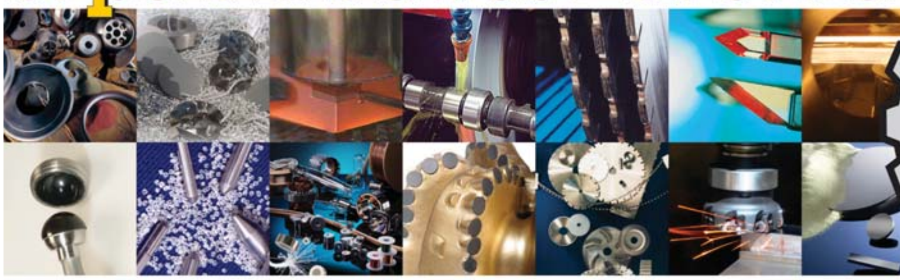
A multi-element high entropy alloy not only tests out as one of the toughest materials on record, but, unlike most materials, the toughness as well as the strength and ductility of this alloy actually improves at cryogenic temperatures.

TIMKEN

TIMKEN RESTRUCTURING, REORGANIZING AEROSPACE BUSINESS

The Timken Company has announced multiple actions it is taking to improve the performance of its Aerospace business. Specifically, Canton, Ohio-based Timken will eliminate the management structure for that business and seek a buyer for its aerospace MRO parts business. More specifically, Timken will close an engine repair and overhaul operation in Mesa, Ariz., and an aerospace bearing plant in Wolverhampton, England. Timken expects to record a non-cash charge of $110 to $120 million in the third quarter of 2014, and will cease reporting separate results for the Aerospace operations. The Arizona plant was developed as a specialty center of parts manufacturing for aerospace engine repairs and refurbishment, including investment casting capability for turbine blades, vanes, nozzles, and turbineengine hardware. "Aerospace has been and will continue to be an important market for Timken," stated Richard G. Kyle, Timken president and CEO. "It fits the Timken Business Model well and we will continue to pursue challenging applications that value our technology and our service. We remain committed to creating value for customers in the aerospace industry and are confident that our efforts will improve the strength of our business for both customers and shareholders going forward," Kyle said. For more information visit: www.timken.com

Superabrasives Education



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OBJECTIVE

"Superabrasive Materials Principles and Applications" is wholly sponsored by the IDA Membership and designed specifically to educate on the use of industrial diamond, cubic boron nitride (cBN), CVD Diamond & cBN, Nanodiamond and polycrystallines classified as superabrasives. It is Non-commercial, unbiased and representative of accepted principles and practices. Content will include a wide range of products and applications for the automotive, aerospace, medical, electronics, optics and other industries using superabrasives. The attendee will be educated in the primary areas of grinding and machining with peripheral explanation for other uses, such as non-abrasive applications.

AUDIENCE

This Course will educate a broad range of engineers, toolmakers, machine operators, suppliers, end users and other interested individuals that currently employ superabrasives in manufacturing operations on how they can optimize their use and expand into other areas and applications. This course will also educate those currently using conventional abrasives to understand the advantages of superabrasives and how they can be applied to increase productivity, reduce scrap and improve the cost effectiveness in manufacturing operations.

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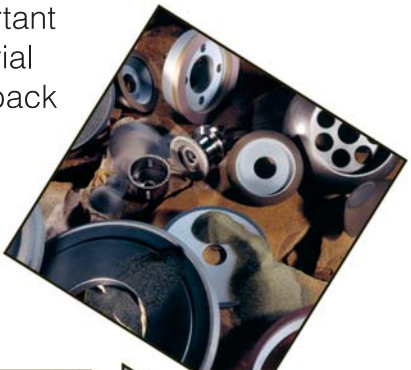
EDUCATION CRITICAL TO MANUFACTURING SUCCESS

Education has been a major topic today across all mainstream news media and trade publications. The US Government has even initiated programs that address the issue of a manufacturing workforce that is seriously lacking in both numbers and skilled labor headcount. With many companies reshoring and a host of others in the midst of building new plants, or retooling existing operations to meet rising productivity demands, new operations have seen an influx of sophisticated machines. To match this technological upheaval, it has become paramount that skilled labor be educated in the characteristics, properties and performance of the new-age abrasives being applied. Education has become one of the most important challenges for every industry and manufacturing operation. The Industrial Diamond Association of America (IDA) has met that challenge. Going back almost seven decades the IDA has set the standard for education and training, beginning with natural diamond first used in carbide grinding applications. Then came the windfall of manufactured superabrasives and the face of manufacturing changed forever. The IDA once again was in the forefront educating an established workforce on the advantages and application of these new materials.



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Polycrystalline Diamond Redefines the Term "WOODWORKING"

By: DAVID G. FREUND, President
Saber Diamond Tools, Inc.

PHOTO 1 – Woodworking now encompasses a wide variety of materials.

Wood was probably one of the very first raw materials used in manufacturing. From the time the first caveman pushed a sharp stone through a stick to create an ax, our civilization has been refining the term "Woodworking". Over the last several thousand years, the concept of working with wood has continued to evolve. This is especially true with the advent of machinery being introduced into the process. What was once a craft performed locally, by hand, has now emerged as a major industry with production sites geared up to mass-produce everyday products which are then shipped thousands of miles to consumers like ourselves. The concept of centralized production has introduced automation, robotics, computers, and numerous other high technology systems to keep pace with the high volumes and speeds which are now being used to manufacture wood products.

The concept of centralized production has introduced automation, robotics, computers, and numerous other high technology systems to keep pace with the high volumes and speeds which are now being used to manufacture wood products.

While it is true that wood is a relatively soft material and the use of Polycrystalline Diamond (PCD) to process wood might seem at first glance to be a little bit of overkill, there is much more to this story than just simply making wood chips. There are three major factors which make PCD the ideal material for use in creating the cutting tools used in the Woodworking Industry. The first is the manufacturing conditions such as the high feed rates and tool RPM's which are now common in the processing of wood. The second is an evolution in the material itself which has greatly expanded what is considered to be termed "wood". The third is the advances in Electro Discharge Machining (EDM) equipment that enables more intricate tool designs that are needed to satisfy the requirements of the first and second factors listed about. All three of these aspects have undergone tremendous changes in the last decade and show every sign of continuing this trend in the future. This need for faster cutting rates in much more difficult to process materials combined with the ability to now EDM in ways that were previously impossible pushes this industry significantly in the direction of PCD tooling.

PHOTO 2 – PCD Tools for Woodworking require very intricate tooth configurations to be able to cut the multi-layer composites effectively.

HIGHER PRODUCTION RATES

Woodworking factories continue a trend toward higher feed rates, expensive automated equipment, lower scrap rates, and the need for very tight tolerances on the finished product. On some production lines, material feed rates in excess of 2500 feet per minute are normal ... That's 30 miles per hour!! It is also routinely expected that the dimensions for a wood product be within .001" of specification. It is unlikely that you would ever notice that your kitchen cabinet or dining room table is .001" shorter, or longer, than you expect. But since the entire production system in these modern woodworking factories is now automated, it is the production process itself that requires this type of accuracy. When each production step depends on the extreme accuracy of the previous steps such as in slitting, sanding, laminating, drilling, trimming, painting, etc, to enable the automation to work properly, it forces this industry to set internal production dimensional standards that go well beyond what is actually perceptible in the final product as seen by the customer.

The fact that PCD maintains its cutting edge 10, 20, 50X or more longer than carbide means that these PCD tooled production lines can run much smoother without issues and the costly downtime related to the constant tool changes necessary due to the significantly shorter life of carbide tooling. While PCD tools are obviously more expensive than carbide tools, the fact that PCD will eliminate 90%, or more, of the machine downtime due to tool changes generally means that the PCD tools pay for themselves in reduced production cost long before they are sharpened the very first time.

Most successful wood processing plants have spent millions of dollars on modernizing their manufacturing lines to utilize the latest technology. They understand that in order to get the best return on a $1,000,000 investment in a modern computer controlled machine, they cannot rely on a $50 carbide tool to do the cutting. The economics of the improved production efficiency more than justifies the cost of PCD tooling and all indicators point to the future trends continuing in this direction.

WOOD WITHOUT TREES

The second evolution in the Woodworking Industry that results in higher demand for PCD is the material itself. When you think of wood you probably think of oak, maple, pine – something that originates with a tree. While the PCD tools we are discussing are used on solid woods, it may surprise you to learn they are more likely to be used on some type of composite or “manufactured wood”. The high demand for wood products, the increasing scarcity of quality wood, and the inherent weakness in wood due to grain orientation has lead to numerous replacements for what was traditionally made of solid wood. In fact, a lot of “woodworking” involves materials that have nothing to do with trees at all. Many of the materials that we use for making furniture, kitchen cabinets, and floors appear to be wood, but have no real solid wood in them. They are made from a substrate of some organic product such as corn husks, wheat straw, wood chips, paper, etc. combined with lots of resin which is then put under high pressure to increase strength. This substrate is then covered with a paper, plastic, or vinyl overlay which is glued to the substrate. Many of these overlays are colored to look very much like solid wood.

PHOTO 3 – The EDM process for making Woodworking Tools relies on very complex cutting and shaping of the PCD edge and the clearance angles.

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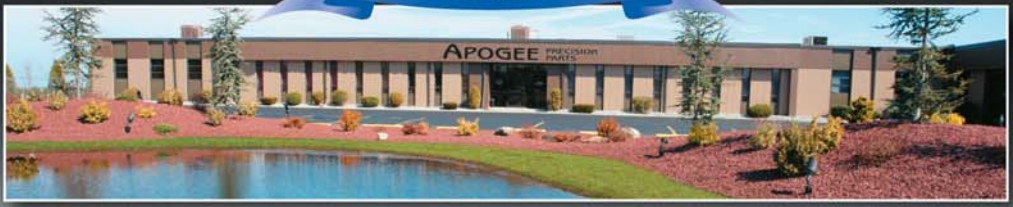

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There are many variations of this process but it generally involves some type of high resin content substrate to provide strength with an overlay to provide the visual appearance required to make it a pleasing piece of furniture. Some of the combinations can get very bizarre as manufacturers try to combine cosmetics with characteristics such as stain resistance, water resistance, fatigue strength, thermal insulation, impact resistance, light weight, scratch resistance, and obviously low cost. So there can be many layers of different materials combined to provide the desired final characteristics of the end product.

For a PCD Toolmaker this composite presents a difficult challenge since the high resinous substrate is very abrasive and the glue line is also abrasive and is very concentrated. The overlay can be a brittle solid surface material which chips easily, a very thin sheet of paper which has a tendency to fuzz or fray, or a vinyl which tends to stretch rather than cut cleanly. Therefore, a PCD cutting edge has to be designed to cut all the layers of materials successfully – with even wear, a clean cut, and to very tight tolerances. This is one of the reasons PCD Woodworking Tools have a fairly complex geometry with several sections incorporating different shear, hook, and clearance angles and may even contain more than one type of PCD to get the desired result. Each of the layers of the composite requires a different geometry on the cutting edge of the PCD tool. This is a difficult challenge, but one that a PCD Toolmaker deals with on a daily basis.

EDM MACHINE TECHNOLOGY

The third aspect of this industry that has had significant impact on the use of PCD is the advancements made in the EDM machinery itself. In order to produce the type of PCD tools with higher shears, more intricate profiles, and less run-out that are needed for this industry, the EDM Machine Builders have now recognized that the Woodworking Industry is not only significant, but also needs its own set of specific manufacturing equipment. When compared to other industries that use PCD tooling, the Woodworking Industry in general requires larger diameter, heavier tools that have a very complex geometry, more intricate shear and clearance angles, and will run at higher feed rates. Until a few years ago, Woodworking Tool makers normally modified existing EDM machines to suit their needs.

But today, several EDM Equipment Manufacturers supply large scale EDM machines that have the capability to produce the shear angles and complex profiles that are needed. They have also incorporated some of the advanced automatic tool and electrode loading features that enable 24x7 manufacturing and more efficient production to help justify the cost of continuing to upgrade the manufacturing technology. So the EDM machine suppliers have now tailored equipment specifically to the Woodworking Industry needs. This has enabled even more complicated tool designs to be possible and allowed the PCD tool makers to successfully penetrate even newer markets segments.

As you can see the Woodworking Industry has really outgrown the term “Woodworking”. Today, most of the raw materials used in the Woodworking Industry are ones that even a tree would not recognize. It would be more accurate to describe it as the “Resin Working Industry”. The trend for the last decade or so, is to utilize more modern materials such as plastics, composites, laminates, carbon fiber, resinous compounds, fiber glass, acrylics, ceramics, etc in more of the items that we use every day which were once the domain of the basic material ... ”Wood”. Some of these newer materials cannot even be successfully cut with carbide tools which makes Polycrystalline Diamond not only the best option, but in some cases the only option.

These trends will continue as we seek stronger, lighter, more cost effective materials which impact a much larger segment than just the general consumer items. The term “Woodworking” with PCD has gone well beyond its original definition and has now become a phrase which applies to many new areas such as aerospace, plastics, electronics, and composites. It is expected that this movement will continue well into the future as stronger, more durable, more difficult to process materials come onto the market. ■

For additional information contact: dfreund@saberdiamond.com

PHOTO 4 – One of the newest technologies, a Vollmer QXD EDM machine, showing the automated tool carrousel loaded with a variety of profiled PCD tool types to enable unattended 24x7 production.

PHOTO 5a & 5b – Advances in exotic materials for consumer products and in the aerospace industry enables the Woodworking Market to “branch out” into many new areas.

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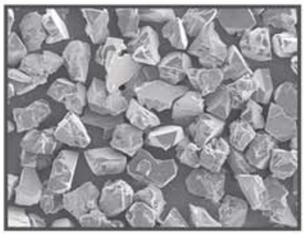

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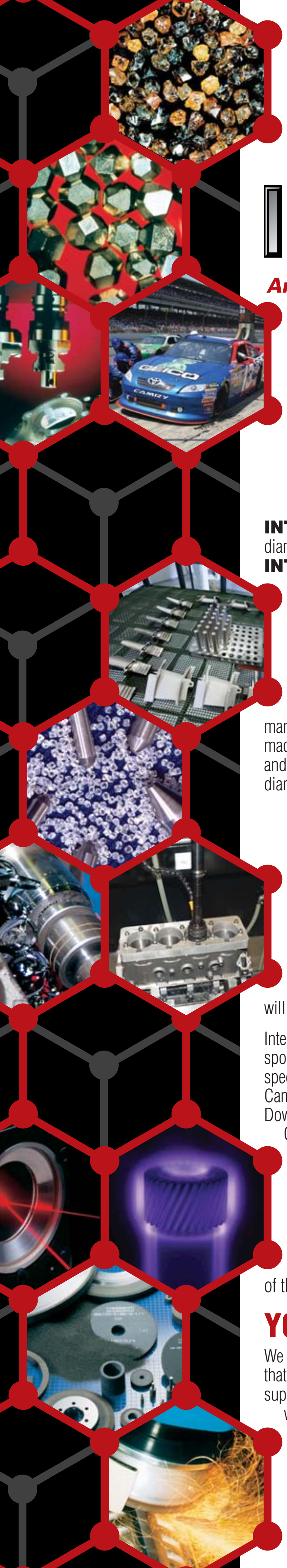

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INDIANAPOLIS IS A MAJOR ATTRACTION…

Over 20 million people will arrive in Indianapolis next year. A few of these will attend **INTERTECH 2015**. In May, Indianapolis hosts the INDIANAPOLIS 500, heralded as The Greatest Spectacle in Racing. It is only appropriate that **INTERTECH**, the greatest spectacle in superabrasives, be held in the same month. **INTERTECH** has been held in many locations over the last 14 years and in 2015 this sensational event will be held in Indianapolis, Indiana USA. **INTERTECH** is known for excellent locations and exceptional service and **INTERTECH 2015** will carry on that tradition at the Indianapolis Marriott Downtown. We are anticipating the usual excellent attention and personal service that has become the standard of **INTERTECH** conferences. The Marriott boasts beautiful accommodations, revamped meeting rooms and luxurious amenities. The Marriott is conveniently located in the center of downtown Indianapolis surrounded by excellent restaurants, attractions and shops. **INTERTECH 2015** will be a rewarding technical experience complimented by this excellent venue.

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We are now soliciting commercial and technical papers of approximately 30-45 minutes in length that address the research of these super-hard materials as well as the dynamics and application of superabrasive systems in automotive and other industries as well (see: Areas of Consideration) with a focus on new technology, tooling, workpiece materials, machines and applications related to increased **PRODUCTIVITY** and **PERFORMANCE**. Consideration for papers is being made at this time and abstracts are now being accepted; contact us today to be considered. This will be the most comprehensive event ever held on super-hard materials for automotive and similar industries!

Photos of Indianapolis for INTERTECH 2015 courtesy of Indianapolis Convention & Tourism Bureau.

AREAS OF CONSIDERATION FOR PAPERS FEATURING PAPERS ON SUPERABRASIVES FOR AUTOMOTIVE

AUTOMOTIVE
- Parts Manufacturing
- Gears
- Wheels
- Transmissions
- Engines

MACHINE TOOLS
- Development
- Innovations
- Advancements
- Superabrasive

RESEARCH & DEVELOPMENT
- New Crystals & Abrasives
- New Coatings
- Bond Development
- Testing/Gauging
- Tool Fabrication
- Materials
- Tooling
- Application Development
- HPHT Technology
- Film (CVD & PVD)
- Magnetorheological Finishing
- Electrolytic In-process Dressing (ELID) Mirror-Surface Grinding
- Nanotechnology

TOOLING
- Grinding Wheels
- Cutting Tools
- Drill Bits

WEAR PARTS
- Rests
- Anvils
- Nozzles

WORKPIECE MATERIALS
- Metal Matrix Composites
- Bi-Metals
- High Tech Ceramics
- High Silica Aluminum
- Glass
- New Materials & Alloys
- Thermal Sprays
- Superalloys
- Nano-Structured Materials

OTHER NEW TECHNOLOGY & APPLICATION DEVELOPMENT

OTHER INDUSTRIES AND TOPICS FOR CONSIDERATION

AEROSPACE
- Manufacturing
- Rebuilding

CONSTRUCTION/HIGHWAY
- Concrete Aggregates & Variables
- Highway/Runway
  - Grinding & Grooving
  - Bridge Repair
- Renovation
- Block Grinding
- Polishing

ELECTRONICS
- Disc Texturing
- Wafer Mfg.
- Polishing
- Optic Windows
- Semiconductors
- Heat Sinks

EMERGING TECHNOLOGY
- CVD Diamond
- Nanodiamond
- New Crystals
- Coatings

GLASS
- Lens Generation
- Polishing
- Pencil Edging

MACHINE TOOLS
- Development
- Innovations
- Advancements
- Superabrasive Adaptation

MEDICAL
- Surgical Knives
- Prosthesis Fabrication

MINING/DRILLING/NATURAL RESOURCE EXPLORATION
- Drills & Bits
- Application

NANOTECHNOLOGY
- Medical Developments
- Industrial Applications
- Electronics
- Other Research & Developments

OTHER MANUFACTURING
- Pumps
- Motors
- Heavy Equipment

OPTICS
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- Diamond Coating

RESEARCH & DEVELOPMENT
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- Electrolytic In-Process Dressing (ELID) Mirror-Surface Grinding
- Nanotechnology

STONE PROCESSING
- Quarrying
- Sawing
- Polishing

SUPPLIERS TO SUPERABRASIVE INDUSTRY
- Metals
- Coolants
- Measuring & Gauging
- Safety
- Pressing Equipment

TOOLING
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WIRE DRAWING
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- Applications
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- Single Crystal
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OTHER NEW TECHNOLOGY & APPLICATION DEVELOPMENT

WATCH FOR INTERTECH 2015 ON-LINE

As you can see by the areas for paper consideration, diamond and cubic boron nitride are not just being used as abrasives in traditional applications. Today, superabrasives and ultra-hard materials are making inroads in electronics, medical, cosmetics and literally every other industry where the characteristics of diamond and cubic boron nitride can affect performance or provide higher strength or new capabilities. As an **INTERTECH** attendee you will learn how these new products and applications are being developed, where super-hard materials are being used and how you can apply these systems in new and innovative ways. Visit the **INTERTECH 2015** website: www.intertechconference.com for additional information on:

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● SPEAKERS & TOPICS ● TABLETOP DISPLAYS ● KEYNOTE ADDRESSES
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On-Line submission of abstracts is now available at www.intertechconference.com. If you wish to present a paper, you can also send a one or two paragraph abstract of your paper topic via email, fax or regular post to: Terry M. Kane, Chairman • INTERTECH 2015 • P.O. Box 29460 • Columbus, Ohio 43229 • Telephone: 614-797-2265 • Fax: 614-797-2264 • e-mail: tkane-ida@insight.rr.com

ABSTRACTS WILL BE ACCEPTED FROM JULY 1, 2014 THROUGH JANUARY 1, 2015

We will reply to all submissions. Come join us! **INTERTECH** has the tradition of being the most comprehensive event held on superabrasives and ultra-hard materials.

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Calendar of EVENTS

To have your event or conference listed, please send information to: Finer Points Event Calendar • P.O. Box 29460, Columbus OH 43229 • Fax 614-797-2264 or email: tkane-ida@insight.rr.com

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October 14-16, 2014
Global Forecasting & Marketing Conference
MGM Grand Detroit
www.amtonline.org/moreinfo/gfmc-2014

October 30 - November 4, 2014
Japan Machine Tool Fair
Tokyo Big Sight (Tokyo International Exhibition Center) Japan
www.jimtof.org

November 10-11, 2014
Concrete Sawing & Drilling Association
Slab Sawing & Drilling 201
St. Petersburg College
Clearwater, Florida USA
www.csda.org

November 12-13, 2014
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November 11-13, 2014
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www.fabtechexpo.com

November 13, 2015
Industrial Diamond Association of America
Superabrasive Materials, Principles & Applications
Education Course
Huntsville, Alabama USA
www.superabrasives.org

December 1-4, 2014
Defense Manufacturing Conference
San Antonio, TX, USA
Henry B. Gonzalez Convention Center
www.dmcmeeting.com

December 9-11, 2014
Hilton La Jolla
Torrey Pines
La Jolla, CA, USA
www.compositesworld.com/conferences/compositesworld-2014-carbon-fiber-conference

Calendar Dates for 2015

May 18, 2015
Industrial Diamond Association of America Annual Meeting

Marriott Indianapolis Downtown
Indianapolis, Indiana USA
www.superabrasives.org

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Issue:	**Editorial Feature*:**	**Closing**
Winter 2013/2014	Materials and Processing	Dec. 1, 2013
Spring 2014	Testing Facilities & Equipment	March 1, 2014
Summer 2014	IMTS Preview, Education Program and INTERTECH 2015 Call for Papers	July 1, 2014
Fall 2014	Diamond and cBN Polycrystalline Materials – INTERTECH 2015	Sept. 1, 2014
Winter 2014/2015	Superabrasive Industry Review INTERTECH 2015	Dec. 1, 2014

***Editorial topics & closings subject to change**

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Correlation of Failure Strength with Magnetic Properties and Material Composition of Polycrystalline Diamond

By: D.K. Mukhopadhyay and K.E. Bertagnolli, US Synthetic Corporation

ABSTRACT

The failure strength of freestanding polycrystalline diamond (PCD) was determined using a burst-disc test. The polycrystalline diamond discs were formed by sintering diamond powder with cobalt infiltration from a cemented tungsten carbide substrate at high pressure-high temperature (HPHT). PCD was produced with diamond grain sizes ranging from 12 to 100 microns. The cobalt content was varied independently by sintering at two different pressures. Measurement of specific magnetic saturation and coercive force were made on each PCD disc and compared to the strength measurements. A model was built from this data to show the relationship between failure strength and the magnetic properties. Diamond grain size and specific permeability (the ratio of the specific magnetic saturation to the coercive force) were found to be accurate indicators of failure strength.

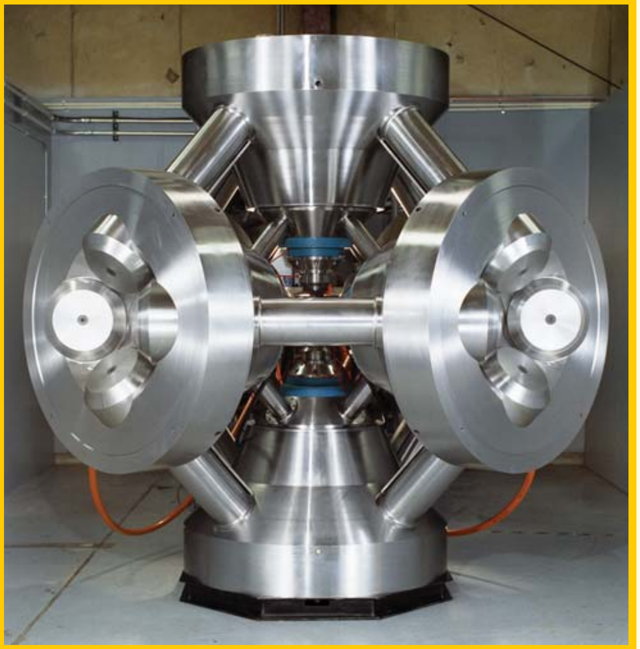
INTRODUCTION

Conventional polycrystalline diamond cutters (PDC) are made by sintering diamond powder on a cobalt-cemented tungsten carbide (WC-Co) substrate under high pressure-high temperature (HPHT) conditions around 6 GPa and 1400°C. During sintering, cobalt from the substrate melts and infiltrates through the pores among the diamond crystals, acting as a solvent-catalyst for diamond formation. The molten cobalt dissolves carbon atoms from the diamond crystals and quickly saturates. DIAMOND AND CARBIDE SUBSTRATE The dissolved carbon precipitates and forms diamond-diamond bonding among the diamond crystals. The sintered polycrystalline diamond (PCD) layer provides abrasion resistance, mechanical HPHT CUBO PRESS strength, and fracture toughness, while the WC-Co substrate provides an interface for attachment.

The diamond table of a typical PDC insert consists of a ferromagnetic cobalt phase and a nonmagnetic diamond phase. A small amount of non-magnetic WC is also present in the diamond table. Thus the PDC diamond table is amenable to magnetic property measurements. Magnetic property measurements have been used to assess quality and consistency of cemented carbides for many years. Both specific magnetic saturation (s_s) and coercive force (Hc) are commonly used for this purpose. The specific magnetic saturation provides a measure of the cobalt content in the diamond table. The coercive force measures the ease with which the ferromagnetic domain walls are aligned by an induced magnetic field. Coercive force has been shown to correlate with mean free path of cobalt in cemented WC. By analogy this should also be a measure of the mean free path of cobalt or degree of diamond intergrowth in PCD.

Since their introduction over 30 years ago, PDC inserts have made a significant impact on the oil and gas drilling industry. Bits equipped with PDC cutters now account for a significant portion of the total footage drilled. High rates of penetration, long life, and simplicity are some of the benefits afforded by PDC bits. However, PDC bits have had limited success at drilling high compressive strength and abrasive rock formations. One of the limitations to hard rock drilling is the propensity of the cutters to break.

New PDC cutter designs must be evaluated for failure strength prior to field application. Lammer showed that the strength of polycrystalline diamond increases as the grain size of the



HPHT CUBO PRESS

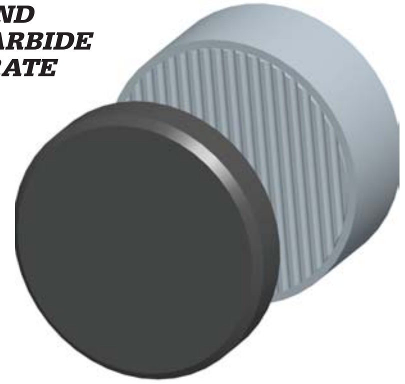
diamond crystals decreases as per the Hall-Petch effect. Cobalt content also increases with decreasing grain size, increasing the strength of the PCD. However, Lammer was unable to determine the influence of the cobalt secondary phase independent of the diamond grain size. This is because the cobalt content cannot be changed for a given diamond grain size under a fixed HPHT condition since it is introduced by infiltration from the substrate rather than mixing.

The present article proposes a novel procedure for evaluating the strength of polycrystalline diamond using magnetic properties. The cobalt content of the polycrystalline diamond was varied independently of the grain size by adjusting the sintering pressure. Magnetic property measurements were used to determine the metal content in the polycrystalline diamond and the cobalt mean free path, which gives an estimation of diamond intergrowth. A parametric survivability model was created to show the relationship between magnetic properties, diamond grain size, and failure strength.

MATERIAL AND METHODS

High pressure sintering was carried out using a cubic-type HPHT apparatus. Temperature was measured with a W5%Re-W26%Re thermocouple without correction for the pressure effect. Pressure was calibrated at room temperature using the known transitions of Bi, Tl, and PbTe. Commercially available synthetic diamond powders with mean particle sizes of 12, 20, 30, 40, 65, and 100 µm were used as the starting material for all samples. The WC-Co substrate contained 13 wt.% Co with WC grains of 2–4 µm. The diamond powder and WC-Co substrate were enclosed in a niobium capsule,

DIAMOND AND CARBIDE SUBSTRATE



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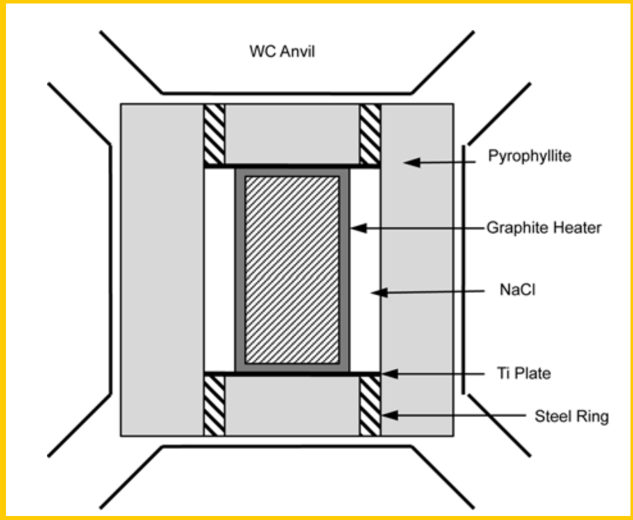

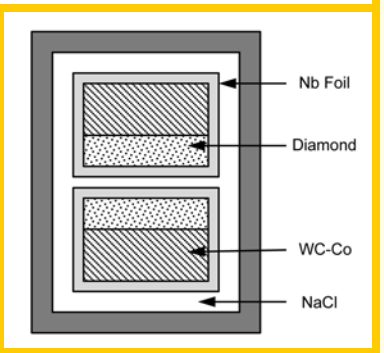

Figure 1. Sample assembly for high pressure-high temperature (HPHT) sintering of diamond. (A) Overall view; (B) enlarged view of graphite heater.

surrounded by sodium chloride, placed inside a graphite resistance heater, and enclosed in a pyrophyllite cube. The cube assembly for high pressure sintering is shown in Figure 1.

The samples were first subjected to a pressure of either 6 or 7 GPa. The temperature was then raised to approximately 1400°C by passing electric current through the heater. The sample was maintained at temperature for approximately 2 minutes. Power was then turned off and the cell was allowed to cool before pressure was released. Typical run times were on the order of 6 minutes. Once sintered, the samples were removed from the cube assembly, and the diamond table was lapped flat. The diamond table was then removed from the WC-Co substrate by grinding. Care was taken to remove residual niobium from the outer diameter and any exaggerated tungsten carbide grain growth from the interface. The magnetic properties of the PCD discs were measured with a Koerzimat 1.096 manufactured by Forester Instruments Inc. A photo of Koerzimat 1.096 is shown in Figure 2. Specific magnetic saturation (s_s), also known as magnetic moment, and coercive force (H_c) of each disc were measured prior to strength testing. Specific magnetic saturation provides a measure of the cobalt content in the diamond discs. Coercive force gives the mean free path of cobalt (distance between diamond grains) in the diamond discs. The ratio of specific magnetic saturation to coercive force (s_s/H_c) is defined in this article as specific permeability. The failure strength of the PCD discs was measured with a burst disc apparatus. The diameter of the diamond disc for burst disc measurements was 15.88 ± 0.02 mm and the thickness was 1.02 ± 0.02 mm. The discs were placed on a hollow cylindrical fixture and were subjected to a hydraulic load. The load increased gradually until the discs failed. The failure strength was measured as burst strength.

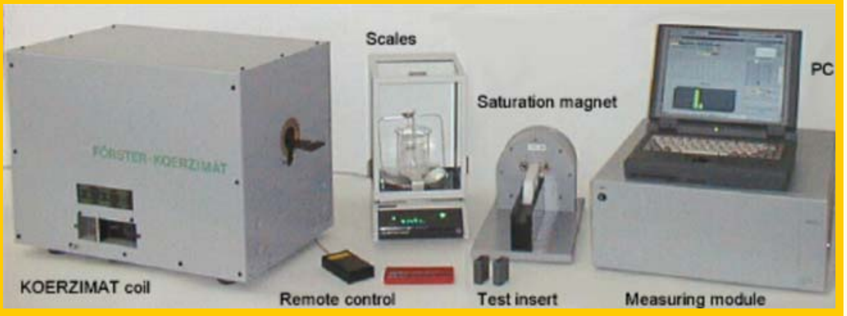

Figure 2. The Koerzimat 1.096 (photo courtesy of Forester Instruments Inc.)

RESULTS AND DISCUSSION

The failure strength of the polycrystalline diamond discs is plotted in Figures 3 and 4. Figure3 shows the results for discs sintered at 6 GPa, and Figure4 shows the results for discs sintered at 7 GPa. A lognormal model provided the best fit to the failure strength data. As expected, the failure strength increased with decreasing grain size. The strength also decreased as sintering pressure increased.

A plot of specific permeability as a function of grain size and sintering pressure is shown in Figure 5. As grain size decreases, cobalt content increases (s_s increases) while mean-free-path decreases (H_c increases). The specific permeability increases as grain size decreases because cobalt content increases faster than mean-free-path decreases. As pressure increases, both cobalt content and mean-free-path decrease, leading to a decrease in specific permeability.

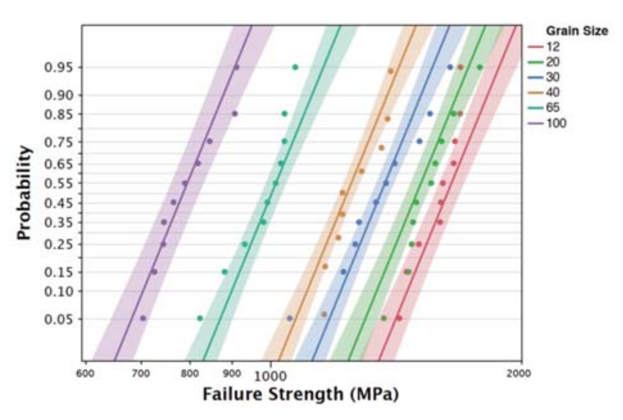

Figure 3. Failure strength polycrystalline diamond discs sintered at 6 GPa

A parametric survivability model based on a lognormal distribution of the failure strength was created. The influence of grain size and specific permeability on failure strength can be seen in Figure 6. Solid lines represent the model predictions. The dashed lines represent the 95% confidence interval around the predictions.

For a given grain size, the failure strength increases as specific permeability increases. One way to increase specific permeability while maintaining grain size is to lower the sintering pressure. The greatest failure strength comes from PCD with fine diamond grain size and high specific permeability. Thus maximizing the amount of cobalt in the PCD produces discs with the highest failure strength. Several factors contribute to the strengthening effect of cobalt. First of all, cobalt is a strong phase by itself, and increasing the fraction of the strong phase leads to increased strength of the composite. In addition, the cobalt creates a compressive residual stress in the PCD disc, which increases strength. Cobalt pools may also act to blunt crack propagation through the diamond table. It was assumed that increased diamond intergrowth would result in higher failure strength. After all, diamond bonds are some of the strongest bonds in nature. Sintering at higher pressure results in more diamond intergrowth as evidenced by lower cobalt content and smaller mean free path (lower specific permeability). A plot of the failure strength as a function of grain size for several levels of specific permeability is shown in Figure 7. This plot was created from the model shown in Figure6 assuming the median strength at failure (50% probability of failure). The failure strength decreases as specific permeability decreases for all grain sizes measured in this study. Therefore diamond intergrowth is not a significant factor in determining failure strength of PCD.

One important caveat is that this study looked at the strength of PCD discs alone and not PDC inserts. The PDC composite produces strong residual compressive stress in the diamond table. This compressive stress may affect the overall strength of the composite.

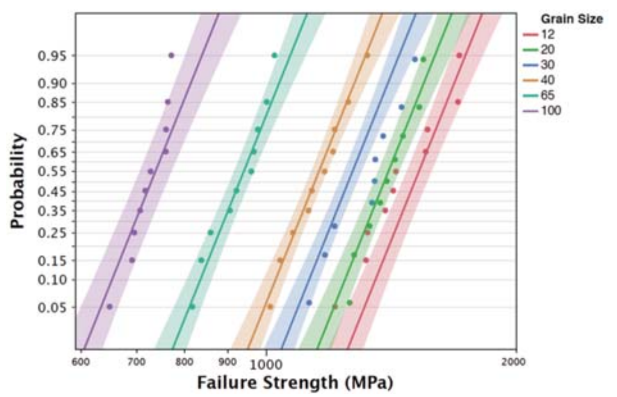

Figure 4. Failure strength of polycrystalline diamond discs sintered at 7 GPa

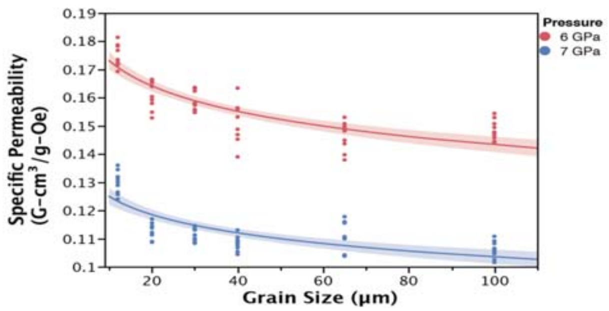

Figure 5. Specific permeability as a function of grain size for polycrystalline diamond discs sintered at different pressures

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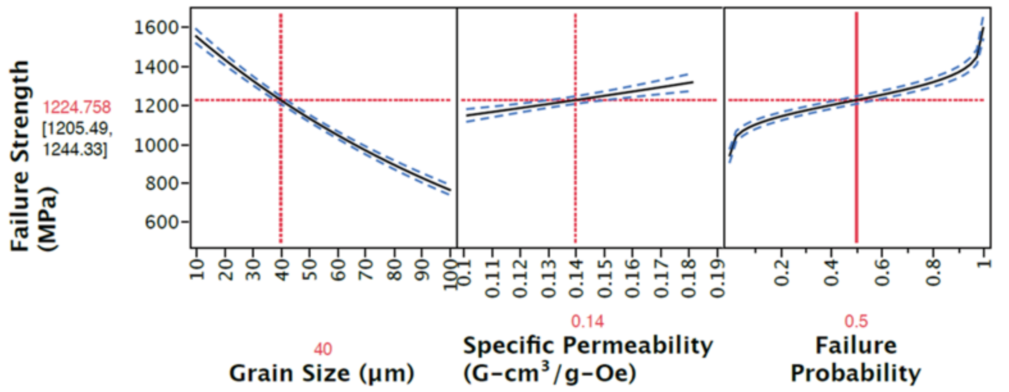


Figure 6. Model result showing the relationship between grain size, specific permeability, and failure strength.

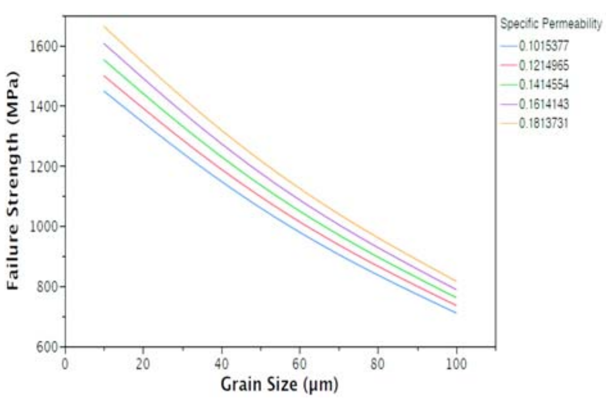
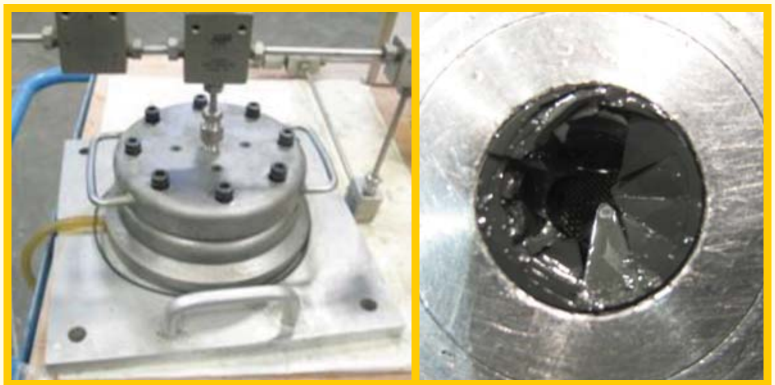


Figure 7 - The relation between grain size and failure strength at different specific permeability

CONCLUSIONS

It is absolutely necessary to evaluate failure strength of PDC inserts prior to field application. In this article an attempt was made to understand the relationship between grain size and magnetic properties of polycrystalline diamond (PCD) discs and their failure strength as measured with a burst disc test. Specific permeability and grain size were both shown to have strong influence on failure strength.

The highest strength PCD discs contain the most cobalt and can be produced by sintering fine grain diamond powder at lower sintering pressures. Surprisingly, increased diamond intergrowth, as evidenced by lower specific permeability, did not increase PCD strength. ■



Rupture strength measured using a burst-disc test unit – Rupture stress calculated from pressure required to break disc

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Efficient Drilling of Advanced Aerospace Materials with PCD Solutions

By: Dr. Qiang Wu, Sr. Engineer, Kennametal Inc.
Fabian Rosenberger, Sr. Engineer, Kennametal Inc.
and Dr. Christoph Gey, Director of Product Development, Kennametal Inc.

INTRODUCTION

Advanced aerospace materials, carbon fiber reinforced plastic (CFRP) alone or stacked with Titanium and Aluminum plates, are widely utilized in aerospace industries for its high strength-weight ratio and stable material properties at demanding environments. Boeing Dreamliner 787 for example, has 80% composites by volume equivalent 50% weight which eliminated 1,500 aluminum sheets and up to 50,000 fasteners, as a result 20% more fuel efficient than Boeing 767. Currently connection technologies for the molded parts like gluing or welding are still under question so that fixturing with rivets is still a dominating reliable process in practice. Due to the substantially different mechanical properties of carbon fibers and metals, drilling fastener holes in those composites challenges cutting tools requiring high wear resistance as well as optimum tool geometries in order to be efficient. Poly-crystalline diamond (PCD) shows great potentials as the cutting tool material in improving machining efficiency compared with traditional tungsten-carbide cutting tools for its high wear resistance in machining of advanced aerospace materials. PCD solid drill thus is developed and offered by some leading metal cutting tool manufacturers. PCD solid drill is a PCD-enhanced solid carbide drill which combines the PCD as the cutting edges onto a solid carbide drill body. The carbide drill body provides the rigidity and the dimensional accuracy to maintain hole qualities. It also enables to add spiral internal coolant holes and helical flutes to improve cooling and chip evacuation necessary for drilling operation. The functional area, cutting edges are made of PCD which provides the wear resistance to enhance machining efficiency.

OVERVIEW

Advanced aerospace materials, carbon fiber reinforced plastic (CFRP) alone or stacked with Titanium and Aluminum plates, are widely utilized in aerospace industries for its high strength-weight ratio and stable material properties at demanding environments. Currently connection technologies for the molded parts like gluing or welding are still under question so that fixturing with rivets is still a dominating reliable process in practice. Machining those materials, however, especially in holemaking operations, challenges cutting tools requiring high hardness as well as optimum tool geometries in order to be efficient. To develop premium solutions for those applications significant attentions are being paid in both academic and industrial practices to improve hole quality and machining efficiency at reduced manufacturing cost. Polycrystalline diamond (PCD) shows its great potentials in such applications replacing traditional tungsten-carbide cutting tools for its high wear resistance. A solid carbide drill with brazed PCD tip for CFRP/Ti stacks is developed and introduced to meet the customers• various needs. The drill has a rigid body with two helical flutes allowing high rake angles. Its integrated PCD tip is made of well-balanced average grain-sized PCD grade to provide excellent wear resistance as well as cutting edge toughness. The drill is manufactured with optimum point geometries to enhance self-centering, hole size and exit burr height control. Internal spiral coolant holes, generated with the new manufacturing technology, can be used for either internal high pressure coolant or minimum-quantity lubricant (MQL) applications. Metal cutting tests show remarkable improvements in tool life, hole quality, and machining efficiency with this one-shot solution in contrast with traditional carbide or veined PCD solutions.

CVD DIAMOND COATED DRILL

CAPPED PCD DRILL

VEIN PCD DRILL

BRAZED PCD DRILL

> ***Advanced aerospace materials, carbon fiber reinforced plastic (CFRP) alone or stacked with Titanium and Aluminum plates, are widely utilized in aerospace industries for its high strength-weight ratio and stable material properties at demanding environments.***

Description	Fine Grain Sized PCD	Medium Grain Sized PCD	Multi-Modal Grain Sized PCD
Grade	G4 (develop.)	KD1415	KD1425
Grain Size	4 µm (average)	10µm (average)	2-30µm (multi-modal mix)
Abrasive Resistance	+	++	+++
Chipping Resistance	+++	++	+
Machinability (erosion, grinding)	++	+++	+

Table 1 – Comparison of Three Different PCD Grades

PCD BRAZING

Optimum tool design is critical to generate good hole quality in machining of advanced aerospace composites. Many essential factors in the course of tool dimensional design play important roles in affecting hole qualities, such as sharper edge radius and larger rake angle to generate lower cutting forces, smaller point angle to reduce less thrust force and fiber delamination, and optimized edge design to improve burr height control. Machine tools, spindle and setup rigidity, tool adaptor, internal or flood coolant, workpiece materials that the drill enters and exits are also important factors need to be considered at tool design. In many cases, customized tools are required to meet various customers' needs in a timely manner.

To develop premium solutions to meet these emerging needs significant attentions are being paid in both academic and industrial practices to improve machining efficiency and hole quality at reduced manufacturing cost. In this article, a brazed PCD solution with optimized drill geometry for drilling of CFRP/Titanium matrix in aerospace is developed. The effect of grain size and microstructure of PCD substrate is investigated to balance hardness and toughness. Brazing technology is introduced to achieve optimum rake angle and reduce manufacturing cost. Tool geometry and its effect are addressed. Experimental study is conducted to compare the PCD grade performance and evaluate the tool overall performance in a contrast with a tungsten carbide drill.

TOOL DEVELOPMENT

To develop a premium PCD enhanced drill, in-depth understanding a suitable synthesis process is necessary. This process development not only determines the tool performance, but also influences the tool's manufacturing efficiency and expenses.

PCD SYNTHESIS TECHNOLOGY

There are four main technologies for producing synthetic diamond based drills for composite materials:

1. CVD Diamond Coated Drill – A finished solid carbide drill is coated with CVD diamond. It is a cost effective solution, however edge sharpness is limited by the coating thickness. Also due to the large difference in hardness between the carbide substrate and the diamond coating this solution has low capacity of absorbing impact energy. Chipping resistance is also limited.

2. Capped PCD Drill – A cone-shaped PCD is sintered onto a small carbide substrate to certain point geometries. The semi-finished component is then brazed onto a solid carbide drill body. This PCD solution is limited in PCD grade optimization due to the necessity of managing high carbide/PCD interface stresses. Post sintering processing can also be costly, as extra efforts taken to remove those diamonds from non-functional areas as well as adding internal coolant holes.

3. Vein PCD Drill – A solid carbide rod with pre-machined slot is filled with PCD precursor powders and then extremely high pressure and temperature are applied to synthesize the PCD structure. After the HPHT process, the rod will be cut, brazed onto a drill body and finally ground to designed tool geometries. This vein PCD technology can generate a complex geometry with high positive rake angles and shape, and requires less grinding than the capped PCD. However, it is limited in size as a result of applying high pressure high temperature onto complex 3D geometry. In addition, normally high cobalt content is needed, thus reducing PCD's hardness and wear resistance consequently.

4. Brazed PCD Drill – 2D is the oldest, most used technology for PCD drills (e.g. spade type PCD drills). For smaller sizes a special carbide sandwiched PCD is used, whereas for the larger sizes individual PCD tips can be used. This solution has serious geometrical limitations as it is difficult to add positive rake angles needed in composite machining applications. The 3D brazing needs a bulk of PCD block of the desired grade and microstructure to be cut in a helical shape as designed. A corresponding helical shaped slot is ground in a solid carbide drill to host the PCD blade. Compared with the capped PCD solution, this 3D brazing only applies PCD on functional areas, thus substantially enhancing machinability. This 3D brazing technology is selected to develop the test PCD drills in this research.

PCD GRADE

The 3D brazing method enables to develop different PCD grades to explore the most suitable grade for the targeted application of drilling CFRP/Titanium aerospace composites. In this tool development, three different PCD grades, G4, KD1415, and KD1425 are investigated (see table 1).

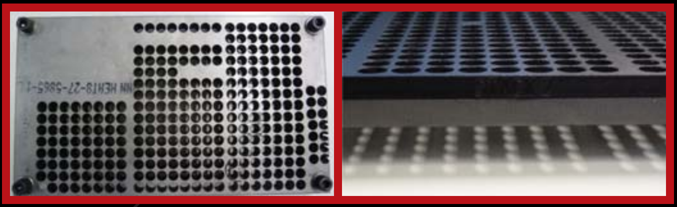
Note: In Table 1, "+", "++", and "+++" stand for low, medium, and high level, respectively. Table 1 shows a theoretical comparison of the three PCD grades regarding abrasive resistance and chipping resistance. Abrasive resistance is a function of diamond particle content (hard phase) and grain size. The larger the PCD grains the more resistant the diamond grade is against abrasive wear which is the dominant wear mechanism when cutting CFRP materials. Unfortunately, large PCD grains negatively affects chipping resistance as larger chunks are being ripped out of the diamond matrix when chipping occurs. Chipping occurs when the mechanical forces on the cutting edge are larger than the inter-matrix bond strength of PCD. Taking these dependencies into account a theoretical rating for these properties has been assigned and will be verified by drilling tests. Another important factor for the choice of a suitable PCD grade is the machinability of the diamond material. The machinability has been rated by measuring manufacturing times for identical tools made from different PCD raw materials. The focus has been set to all manufacturing steps involving PCD disc erosion and PCD grinding. The results of this machinability test are being displayed in the rating in Table1. The better the machinability the higher the rating as faster manufacturing times relate to less expensive manufacturing cost which are equally important as tool performance in order to develop a competitive tooling solution.

PCD BRAZING

As the tool being introduced in this article requires a braze joint of a helically cut slice of the PCD raw material into a tungsten carbide body a brazing technology needs to be chosen that prevents graphitization of the metastable poly-crystalline diamond but also allows bonding of PCD to tungsten carbide. For being able to achieve said bonding an active brazing technology needs to be utilized. An active braze material usually includes higher melting compounds like Titanium. Therefore the brazing temperatures are higher which negatively affects stability of the diamond phase. In order to prevent graphitization an oxidizing atmosphere needs to be shut out during brazing. State of the Art technologies include induction brazing using Argon atmosphere and vacuum brazing.

OPTIMUM TOOL GEOMETRY

Choosing the optimum tool geometry for drilling Composite/Titanium stacks is difficult as the two cutting materials require different drill features. Drilling CFRP is normally being done utilizing high helix angles and long cutting edges as carbon fibers should be sheared along the cutting edge. Long cutting edges are being realized by low point angles. Additionally CFRP drills should induce low axial forces in order to avoid exit delamination. All this translates in rather sharp cutting geometries with small wedge angles. Typical clearance angles go as high as 20 degrees with helix angles around 30 degrees. Cutting Titanium can in principal also utilize a sharp cutting edge, however compared to CFRP drilling a more stable wedge angle is needed. Typical clearance angles for Titanium applications are in the range of 8 to 14 degrees. Compared to steel machining these clearance angles are typically higher (in the presented case around 12 degrees) as heat development on the clearance face should be minimized in order to decrease flank wear. As high clearance angles



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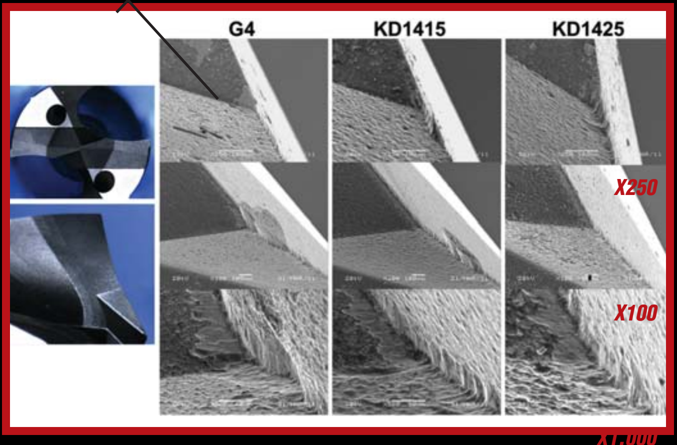

Figure 1 – Unused PCD drills (Grade of G4, KD1415, and KD1425) SEM photos taken at drill corder (X250), gash (X100), and flute surface (X1,000).

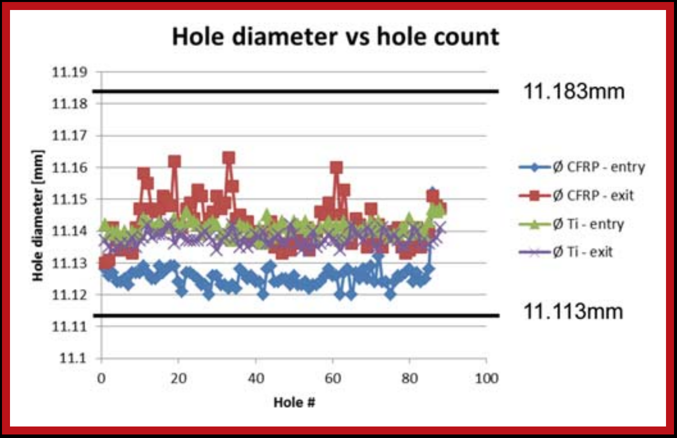

Figure 2 – Hole Count vs. Diameter Exemplary for a PCD Tool (KD1415 – Tool 3)

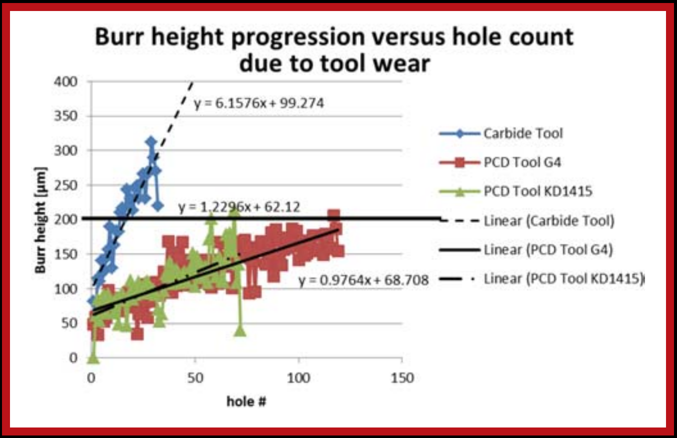

Figure 3 – Burr Height Progression versus Hole Count Due to Tool Wear

Grade	G4	KD1415	KD1425	Carbide
Starting Burr Height (µm)	59-74	67-76	76-85	100-120
Burr Height Increase per Hole (µm)	1,0-1,2	1,0-1,4	1,0-1,2	5,8-6,2

Table 2 – Starting burr height and burr height progression for different grades showing minimum & maximum values for three tested tools of same grade.

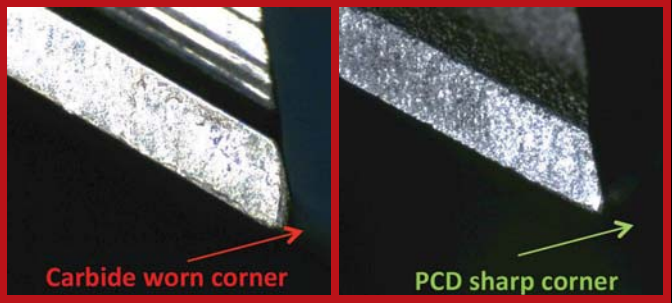

Figure 4 – Carbide Drill's Worn Corner vs. PCD (KD1415) Drill's Sharp Corner After 24 Holes

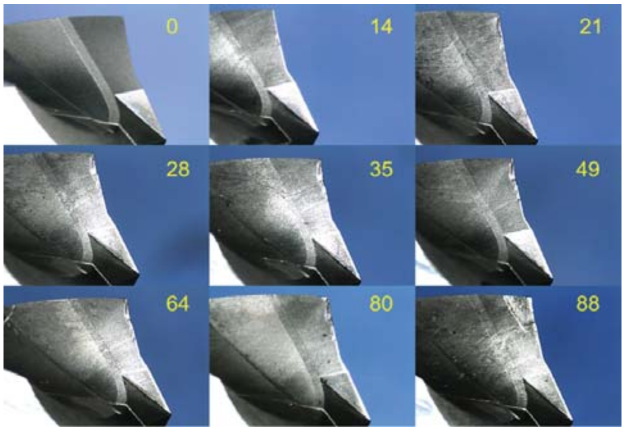

Figure 5 – Wear Progression on the KD1415 (Drill 3), after 0, 14, 21, 28, 35, 49, 64, 80 and 88 Holes

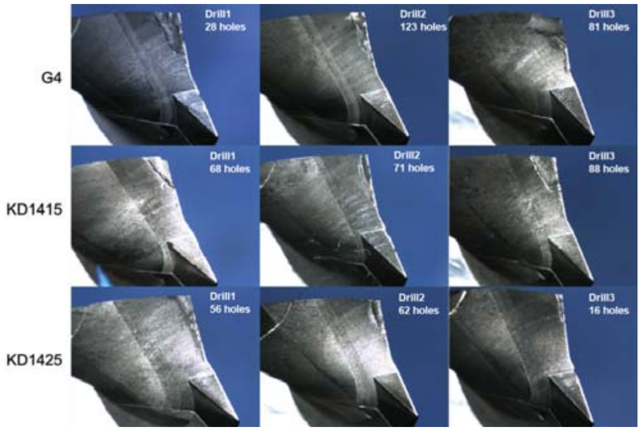

Figure 6 – Failure Mode on All Tested PCD Drills

in combination with typical helix angles of around 30 degrees would weaken the cutting edge too much the helix angle has been lowered to the range of 15 to 20 degrees in order to counterbalance for utilizing high clearance angles. The presented manufacturing technology allows for variable helix angles depending on the tool geometry needs. This is one of the most important advantages of the presented technology as typical corner tipped PCD tools only allow for helix angles up to 8 degrees.

In order to achieve tight hole diameter tolerances it is absolutely necessary that the drill point has an excellent self-centering capability. From another perspective, point angle also plays a significant role on burr formation. It is known that either below 90 or above 150 degrees point angles help minimize hole exit burr height. A drill with a point angle of 155 degrees would therefore be suitable for Titanium exit needs but does not have good centering capability. Therefore a double point angle design is proposed with an inner point angle 130 degrees and an outer point angle with 155 degrees. The overall point height of such a drill is rather short compared to usually used drills with long cutting edges. This brings the 3rd and 4th margin in contact with the material very quickly helping to keep tight hole tolerances. Another advantage of the proposed drill design is the internal coolant capability. For drilling pure CFRP plates, internal coolant holes help to quickly transport CFRP dust out of drill flutes via compressed air. For cutting CFRP/Titanium stacks, minimum quantity lubrication (MQL) can be applied using those sealed internal coolant channels to provide lubricating and to reduce the tremendous heat generated in titanium machining due to its low thermal conductivity. When drilling with PCD tools using MQL is absolutely necessary as otherwise extensive heat at the cutting edge leads to graphitization or TiC formation respectively. This reaction leads to chemical wear in the flute region and finally PCD chipping in flutes.

EXPERIMENTAL STUDY

The developed PCD tools are tested experimentally with the purpose evaluating the most suitable PCD grade and tool geometries for the targeted applications. The test setup and cutting parameters are briefly introduced.

1. Test Tools – Brazed PCD drills, diameter of 11.113mm (7/16"), with three different PCD grades (G4, KD1415, and KD1425) and an uncoated solid carbide drill with the same geometry are chosen as test tools.

2. Test Coupon – Test coupon consists of an 8.7mm (0.342") thick commercially purchased CFRP (Isocarbon 3K) plate securely stacked with a 10.8mm (0.425") thick Ti-6Al-4V plate. Test tools drill through holes, entering the CFRP side and exiting from the Titanium side.

3. Machine Tool and Coolant – A CNC machining center (Heckert CWK 400) with a horizontal spindle is selected as the machine tool. Through spindle MQL coolant (Vascomill MMS FA2) is applied.

4. Cutting Parameters – Cutting parameters of 20 m/min (65 SFM) cutting speed and 0.05 mm/rev (0.002"ipr) feed rate for both CFRP and Titanium are chosen. No pecking cycles were used.

5. Tool inspection – In order to monitor the tool wear progression, test drills were inspected under microscope after drilling of every 4 holes. Wear mechanism inspection was conducted under SEM after drilling of 24 holes. Figure1 shows an unused PCD drills' geometry, corner (X250), gash (X100), and flute surface (X1,000).

6. Hole measurement – After all machining tests, test coupons were cleaned and marked. All drilled holes were inspected. Hole diameter was measured at four depths of each hole (two in the CFRP layer near the entry and exit surfaces, and two in the Ti layer in the same manner). Hole exit burr height on the Ti bottom surface was also measured.

RESULTS AND ANALYSIS

A long, predictable, and consistent tool life is the key factor of deciding a tool's success. In drilling of CFRP/Ti composite matrix, several requirements have to be met simultaneously to accept a good hole, such as the hole size must be within a tight tolerance to well fit a fastener and exit burr must be controlled within certain height to ease or eliminate deburr. To avoid potential hole damage by tool's catastrophic failure and try to keep the tool reconditionable, corner chipping must be minimum and monitored. The following criteria are chosen to decide whether the test tool reaches it end of tool life: Hole size tolerance of 11.113 + 70µm (H10); Burr size of 0.2 mm;

CORNER CHIPPING OCCURRENCE

Test results show that corner chipping was the primary failure mode for the PCD drills at the end of life; and the carbide drill failed by exceeding burr height specification. Hole quality requirements could be met for all drilled holes in this test.

1. Hole Size – Figure 2 shows the hole diameters exemplary for one tested PCD tool. For each inspected hole, the hole diameter was measured at four different positions, two were in the CFRP section and two were in the Titanium section, close to the hole entry surface and the bottom exit surface respectively. It can be seen that the hole diameter in the Titanium layer is very well within the middle of the specified tolerance fluctuating in a small range of 10µm. Hole size at the entry of the Ti layer is pretty close to the size at the hole exit. In the CFRP layer, however, there is a relatively large difference in hole size between entry and exit. This difference is the result of chips scratching the hole wall during evacuation. Improve chip control is essential to reduce chip scratching and enhance the hole size consistency within a hole. It is difficult to solve the chip control issue by tool design only. It is proven in practice that adding pecking cycles or vibration assisted drilling will help to control the chip length and decrease the scratching effect. The results indicate that the proposed new drill point design is capable of creating holes in H10 tolerance. Using optimized machining conditions even H8 hole tolerance levels are achievable with good process reliability. A dependency of hole quality on cutting edge material could not be seen. PCD and carbide tools with the same drill point geometry create similar hole quality results.

2. Burr Height – A clear dependency on drill cutting edge material can be shown when discussing drilling results in regards to burr height control and wear mechanisms. Figure3 shows the burr height progression versus hole count exemplary for a carbide and two PCD (grade KD1415 and G4). It can be seen that a carbide drill creates too large Titanium exit burrs after only 14 hole whereas the first hole out of specification for the two PCD drills are at 57 and 117 holes, respectively. As the burr height measurements for the tools show large scatter, the data points have been analyzed by assuming a linear wear progression due to progressing tool wear, as shown in Table 2. This analysis shows that starting burr height as well as burr height progression for carbide tools in comparison with PCD tools starts higher and progresses 5-6 times faster. Starting burr heights for the different PCD grades show an increasing trend from G4 via KD1415 to KD1425 indicating that finer grain sized materials can be machined with sharper cutting edge geometries leading to low starting burr heights. The burr height increase per hole for the different PCD grades is about the same level (<1.5). In theory burr height progression should be a function of corner wear of the cutting tool. This can be shown between carbide and PCD due to the big difference in material hardness and therefore the slower progressing corner wear on PCD tools, as shown in Figure 4. The PCD drill has much less corner wear than the carbide drill. The difference in the wear progression among the three PCD grades seems to be minor. The dominating wear pattern of PCD grades is the cutting edge/corner chipping. Figure 4. Carbide drill's worn corner vs. PCD (KD1415) drill's sharp corner after 24 holes.

3. Wear and Failure Mechanism Analysis – Tool wear mechanism and wear progression on PCD drills were closely monitored and analyzed during the tests. It was found the same wear pattern, edge chipping, crossed all the tested PCD drills. Figure5 shows a typical wear progression on the KD1415 No.2 drill from new to the end of life (88 holes). Photos were taken at test intervals (0, 14, 21, 28, 35, 49, 64, 80, 88 holes) to illustrate the drill corner, main cutting edge, gashing, point, and flute surface. It can be observed that the cutting edge was smooth when the drill was unused. After 14 holes were drilled, multiple micro fractures initiated on the main cutting edge while the rest of the drill still looks intact. Then those micro fractures gradually connected and extended into flutes in the rake face which could be clearly identified as edge chipping as shown in the image after 21 holes. The formed edge chipping was fairly stable for quite a few holes (from 21 to 80 holes). Finally the chipping ended at the drill corner and margin within eight holes resulted in a catastrophic corner failure. The end of life criteria of (c) is reached. As said, other test PCD drills showed the same wear pattern but varied in width and depth of edge chipping and how fast the edge chipping progressed to the final catastrophic corner failure. Figure 6 shows the end of life images of all tested PCD drills. All tested PCD drills failed as excessive corner chipping while hole quality still meets targeted requirements.

4. Tool Life – Table 3 gives an overview of the tool life results of the three tested PCD grades. As can be seen G4 and KD1415 are very similar in regards toAverage tool life. KD1415 shows more consistent tool life as well as the best machinability to reduce manufacturing cost, therefore chosen as the most suitable grade for this application. ■

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CONCLUSIONS

Brazed PCD solid carbide drills with three different PCD grades and optimum tool geometries were developed and tested. The conclusions of this work are as follows: 3D brazing technology allows manufacturing of PCD tools with flexible helix and therefore large rake angles. Compared with capped PCD solution, 3D brazing enhances machinability by removing less PCD from functional faces. With the optimum tool geometry (double point angle, helical flutes, internal spiral coolant channels, large rake angles), the developed PCD drills were able to generate good hole qualities (hole size diameter and burr height control). Compared with uncoated solid carbide drills, PCD drills show significant improvement in tool life. All tested PCD drills have the same wear pattern which starts off from micro fractures in the rake face, and finally ends with catastrophic corner chipping. KD1415 outperformed G4 and KD1425 in consistent tool life and better machinability. Therefore, KD1415 was chosen as the most suitable grade for this application.

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2921 NW Commerce Park Dr., Boynton Beach FL 33426
Tel. 954-828-9650 | info@worldwidesa.com | wwsa.com

Worldwide Solids, LLC Sales Office
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Element Six US Corporation,
35 West 45th St., New York, NY 10036, USA
Tel: +1 (212) 869 5155
Fax: +1 (212) 764 0349
Email: usadvancedmaterials@e6.com
www.e6.com/ABN900